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Research Article

Noise-Vocoded Sentence Recognition and the Use of Context in Older and Younger Adult Listeners

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ABSTRACT

Purpose: When listening to speech under adverse conditions, older adults, even with "age-normal" hearing, face challenges that may lead to poorer speech recognition than their younger peers. Older listeners generally demonstrate poorer suprathreshold auditory processing along with aging-related declines in neurocognitive functioning that may impair their ability to compensate using "top-down" cognitive–linguistic functions. This study explored top-down processing in older and younger adult listeners, specifically the use of semantic context during noise-vocoded sentence recognition.

Method: Eighty-four adults with age-normal hearing (45 young normal-hearing [YNH] and 39 older normal-hearing [ONH] adults) participated. Participants were tested for recognition accuracy for two sets of noise-vocoded sentence materials: one that was semantically meaningful and the other that was syntactically appropriate but semantically anomalous. Participants were also tested for hearing ability and for neurocognitive functioning to assess working memory capacity, speed of lexical access, inhibitory control, and nonverbal fluid reasoning, as well as vocabulary knowledge.

Results: The ONH and YNH listeners made use of semantic context to a similar extent. Nonverbal reasoning predicted recognition of both meaningful and anomalous sentences, whereas pure-tone average contributed additionally to anomalous sentence recognition. None of the hearing, neurocognitive, or language measures significantly predicted the amount of context gain, computed as the difference score between meaningful and anomalous sentence recognition. However, exploratory cluster analyses demonstrated four listener profiles and suggested that individuals may vary in the strategies used to recognize speech under adverse listening conditions.

Conclusions: Older and younger listeners made use of sentence context to similar degrees. Nonverbal reasoning was found to be a contributor to noise-vocoded sentence recognition. However, different listeners may approach the problem of recognizing meaningful speech under adverse conditions using different strategies based on their hearing, neurocognitive, and language profiles. These findings provide support for the complexity of bottom-up and top-down interactions during speech recognition under adverse listening conditions.

Adverse listening conditions pose significant challenges to speech recognition (Mattys et al., 2012). Broadly speaking, adverse listening conditions may vary in origin but refer to factors that adversely affect the speech perception process, such as noisy environments or listening to a talker with an unfamiliar accent (Mattys et al., 2012; McLaughlin et al., 2018). When faced with adverse listening conditions, older adults, even those with "age-normal"

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auditory pure-tone thresholds, face challenges that may lead to greater decreases in speech recognition than their younger normal-hearing (NH) peers. First, older listeners generally demonstrate poorer suprathreshold spectrotemporal processing of auditory input (Fitzgibbons & Gordon-Salant, 1994; Ruggles et al., 2011; Schmiedt, 2010; Tun et al., 2012; Venezia et al., 2020). Second, older adults experience aging-related declines in neurocognitive functions of working memory capacity, inhibition–concentration, information-processing speed, and nonverbal reasoning (i.e., "fluid intelligence"), all of which may contribute to poorer speech recognition abilities in older listeners (Arehart et al., 2013; Pichora-Fuller & Singh, 2006). In fact, prior studies have demonstrated greater detrimental effects of adverse listening conditions on older listeners with NH than on their younger peers, across speech recognition tasks in numerous adverse conditions, including speech-shaped noise (Grose et al., 2016), multitalker babble (Schoof & Rosen, 2014), and high-variability speech (Sommers, 1997).

Use of Context as Top-Down Compensation

Although these adverse conditions may be particularly deleterious for older adult listeners, there is ample evidence that older listeners are able to compensate, at least to some degree, for this listening adversity using cognitive mechanisms (Başkent et al., 2016). A prominent example in the literature of this type of compensation is "top-down" processing through use of supportive context (e.g., semantic and syntactic constraints) during speech recognition, in which listeners capitalize on their linguistic knowledge to make sense of ambiguous speech under adverse conditions. This concept of top-down compensation is shared among multiple models of speech recognition, wherein the acoustic–phonetic features of the speech input (i.e., "bottom-up" processes) interact with the long-term linguistic knowledge of the listener (Grossberg & Stone, 1986; Luce & Pisoni, 1998; McClelland & Elman, 1986; Morton, 1969; Norris et al., 2016; Tuennerhoff & Noppeney, 2016). Under certain adverse listening conditions, relative reliance on bottom-up versus top-down processes may shift, with the listener depending more heavily on semantic and syntactic constraints (Kalikow et al., 1977; Luce & Pisoni, 1998; Mattys et al., 2009; Rönnberg, 2003; Rönnberg et al., 2013).

As a result of their relative deficits in spectrotemporal processing and neurocognitive functioning, it would seem that older adult listeners even with age-normal hearing thresholds are at a disadvantage when recognizing speech under adverse conditions compared with their younger NH peers. More specifically, because neurocognitive resources play a role in top-down compensation, older adults might be expected to demonstrate poorer use of semantic context than their younger peers. However, some neurocognitive and linguistic abilities that may support use of context are maintained or even enhanced in older age. For example, "crystallized intelligence," the ability to use knowledge that was previously acquired through education and experience (e.g., vocabulary knowledge) is typically maintained with older age (Park, 2002; Salthouse, 1993; Wingfield et al., 1994). As a result, older adults may rely upon crystallized intelligence to overcome adverse listening conditions to the same degree as, or even more than, their younger peers (Balota & Duchek, 1991; D. M. Burke & Harrold, 1988; Daneman et al., 2006; Hopkins et al., 1995; Light et al., 1991; Pichora-Fuller et al., 1995; Price & Sanford, 2012; Sheldon et al., 2008; Wingfield et al., 1994).

However, the previous literature on the impact of aging on top-down compensation is inconclusive. Some studies have demonstrated that older adults capitalize on context to lesser degrees than their younger peers. For example, older adults have been shown to be slower and less successful than younger adults in using predictive contextual information during recognition of sentences degraded by jittering (Pichora-Fuller, 2008). When measuring brain event-related potentials (the N400 response) to constraining sentence-level information, a smaller effect of sentence-level constraint on the N400 response (i.e., a relatively decreased use of sentence context) has been found for older compared with younger listeners responding to visually presented sentence stimuli (Federmeier & Kutas, 2005). Similar studies using the N400 response have likewise demonstrated relative decrements in performance for older adults as compared with their younger peers when provided with sentence context information through either visual or auditory presentation (Gunter et al., 1992; Kutas & Iragui, 1998; Woodward et al., 1993).

In contrast, other studies have demonstrated that older adults may use semantic context more than their younger peers when presented with degraded auditory speech input (Madden, 1988; Pichora-Fuller, 2008; Pichora-Fuller et al., 1995; Stine & Wingfield, 1994; Stine-Morrow et al., 1996). Madden (1988) compared the ability of young adults and older adults to perform visual lexical decision of a target word/nonword (letter string) at the end of a sentence. Targets were either degraded (via asterisks placed between letters) or intact and with congruous or incongruous semantic presentations (i.e., with or without semantic context). Age-related differences in lexical decision speed were greater for degraded targets versus intact targets, and the performance benefit provided by context was greater for older adults compared with young adults. For auditory target word identification performance, Pichora-Fuller et al. (1995) demonstrated that older listeners derive more benefit from context compared with young listeners. In that study, the Revised Speech Perception in Noise (R-SPIN)

Test was presented in varying background noise, and listeners were instructed to recall the sentence-final words in either high-context or low-context sentences. Older and young listeners displayed differences in psychometric functions (percentage of correct word identification as a function of signal-to-noise ratio) in high- versus low-context conditions. Maximum context benefit was found for older listeners in conditions of less severe signal degradation (higher signal-to-noise ratio). Pichora-Fuller et al. (2007) also used temporal jitter to degrade low- and high-context sentences in old and young listeners; interestingly, the two age groups performed similarly in degraded low-context sentences, but older adults performed better in degraded high-context sentences. The authors discussed that this may be due to better use of lexical knowledge during word recognition and more practice using context in adverse listening conditions (Pichora-Fuller et al., 2007). Sheldon et al. (2008) used noise vocoding to test older and younger NH listeners in their use of supportive context for recognizing sentences and target words with or without signal degradation, and the older listeners were found to derive more benefit from context. Similarly, Sommers et al. (2015) have demonstrated that older adults show greater improvements in spoken word recognition than their younger peers when comparing recognition of isolated words with recognition of words in meaningful sentences. More recently, Amichetti et al. (2018) examined the effects of semantic context on word recognition in adult cochlear implant (CI) users. There, older CI users gained a greater benefit of context over younger CI users; interestingly, however, older CI listeners showed a greater degree of interference from other words that might be activated by the context. The authors of that study suggested that age-related deficits in inhibitory control may therefore contribute to variability in use of semantic context among older adult CI users. Lastly, recent work by Failes et al. (2020) demonstrated that older adults are more susceptible than younger adults to "false hearing" (i.e., context-based misperceptions in hearing), which may be due to their weaker ability to inhibit a prepotent response that is favored by context.

Finally, other studies have demonstrated equivalent benefit from context in older and younger listeners (Dubno et al., 2000; Kalikow et al., 1977; Smayda et al., 2016). Kalikow et al. (1977) presented to old and young listeners with NH high- and low-predictability sentences with a target word in both quiet and with background noise. Performance on both conditions for the older adults was slightly poorer than for the younger participants, which the authors suggested may be due to slightly poorer hearing and/or worse cognitive functions. However, the difference in scores between the low- and high-predictability sentences was similar between listener groups. They concluded that the older patients were as adept as young listeners in using semantic context.

Due to variability in the sample populations studied, the adverse listening conditions tested, the measures used, the methods of signal degradation, and the context manipulation techniques, it remains unclear whether older adults use top-down semantic context less than, more than, or equivalently to their younger peers. Taken together, the conflicting findings of the previous studies support the need for additional studies on this topic.

Individual Differences in the Perception of Noise-Vocoded Speech

One goal of this study was to examine top-down context benefits during sentence recognition in older and younger individuals listening to noise-vocoded speech. Most previous studies examining the use of semantic context in adverse listening conditions have involved speech that is presented in noise or babble, which in some ways resemble everyday types of adverse listening conditions with which older listeners have a great deal of real-world experience. Much less has been done to examine how older adults make use of sentence context in recognizing speech that is completely novel to the listener, such as speech that has been spectrally degraded through noise vocoding. This type of spectral degradation is of particular interest to clinicians and scientists in the field of hearing research, because noise vocoding is often used as a model (albeit imperfect) of the spectral degradation that occurs for listeners with CIs. These devices deliver a spectrally degraded signal to the cochlear nerve by providing the temporal envelope of the speech signal divided across approximately 20 electrodes on an electrode array positioned within the cochlea. The effective number of channels of information actually delivered is closer to four to seven, due to spread of excitation from adjacent electrodes, resulting in overlapping regions of neural excitation (Friesen et al., 2001). Over the past 3 decades, noise-vocoded speech has been a valuable research tool for investigating how spectral degradation affects speech recognition in NH individuals, with potential relevance to understanding speech perception in CI users. Moreover, use of noise-vocoded speech supports studying how NH listeners cope with an experimental adverse listening condition with which listeners should not be familiar from everyday life (Eisenberg et al., 2000; Neger et al., 2014; Shannon et al., 1995; Sheldon et al., 2008).

Older adults have generally been shown to have poorer recognition of noise-vocoded speech as compared with their younger peers (Moberly et al., 2018; Neger et al., 2014; Rosemann et al., 2017). Less accurate noise-vocoded sentence recognition has been found to be at least partially attributable to age-related declines in both auditory processing abilities and specific neurocognitive functions, including working memory capacity, inhibition–concentration, speed of lexical access, and nonverbal reasoning (Moberly et al., 2018). The ability to store, integrate, and process new information with previously stored information in working memory (Baddeley, 1992; Daneman & Carpenter, 1980) has repeatedly been identified as a predictor of speech recognition in adverse listening conditions (Akeroyd, 2008; Arehart et al., 2013; Moberly et al., 2017; Rönnberg et al., 2013). More specifically, Schvartz et al. (2008) demonstrated a correlation between verbal working memory capacity and noise-vocoded speech recognition skills in NH listeners. With regard to use of semantic context, Federmeier and Kutas' (2005) study demonstrated that the peak latency of the N400 response (used to gauge response to constraining sentence-level information) was associated with a reading span measure of working memory capacity in their group of older adults, suggesting a relationship between working memory capacity and use of semantic context during sentence recognition.

As listeners process the incoming speech stream, lexical competitors (i.e., items in lexical neighborhoods; Luce & Pisoni, 1998) are activated and must be inhibited (Sommers & Danielson, 1999). Consequently, inhibition–concentration may be a second neurocognitive factor that supports recognition of noise-vocoded sentences by inhibiting lexical competitors, and it is known that inhibitory control both declines with advancing age and relates to speech perception abilities in older adults (Dey & Sommers, 2015). More specific to making use of sentence context, Sörqvist and Rönnberg (2012) demonstrated that inhibition–concentration may help the listener to resolve semantic confusions under adverse listening conditions. Finally, as discussed above, Amichetti et al. (2018) suggested that inhibitory control impacted how well older CI users make use of semantic context, as older listeners showed a greater degree of interference from other words that should be activated by the context of the sentence.

A third neurocognitive function that likely contributes to noise-vocoded sentence recognition is information-processing speed, which is known to be related to performance on complex cognitive tasks such as reasoning and language comprehension (Salthouse, 1996; Verhaeghen & Salthouse, 1997; Wingfield, 1996). Carroll et al. (2016) manipulated both sentence complexity and intelligibility, such that listeners heard canonical and noncanonical sentence structures presented in silence and in background noise. Although not using vocoded speech, they assessed reaction time to different parts of speech and highlighted the important role of information-processing speed, especially when the acoustic signal was degraded. More specifically, information-processing speed for linguistic information—speed of lexical access—is a likely contributor to successful speech recognition (Marslen-Wilson, 1993; McClelland & Elman, 1986). Information-processing speed likely contributes to both rapid binding of the auditory input into phonological representations, along with the efficient use of top-down processing based on semantic context. Thus, speed of lexical access may contribute to the ability to recognize vocoded sentences and the ability to make use of sentence context.

A final neurocognitive resource to consider during sentence recognition processing is nonverbal reasoning (i.e., fluid intelligence). Nonverbal reasoning tasks measure the ability of the participant to solve problems, using awareness of the relations between multiple items in a task, such as Raven's Progressive Matrices Test (Raven, 1938, 2000). In particular, nonverbal reasoning may relate to participants' perception of wholes, memory, and speed of perception (Rimoldi, 1948). Several studies have demonstrated associations between nonverbal reasoning abilities and speech recognition in adult CI users (Holden et al., 2013; Knutson et al., 1991; Mattingly et al., 2018). Similarly, a study by Moberly et al. (2018) demonstrated that performance on Raven's Progressive Matrices explained about 25% of the variability in noise-vocoded sentence recognition in adult listeners. However, nonverbal reasoning has not specifically been assessed as a predictor of the use of semantic context during vocoded sentence recognition.

This study was modeled after a recent study by Moberly and Reed (2019) on sentence recognition by adult CI users. In the Moberly and Reed study, 41 experienced adult CI users were tested for recognition of two types of sentences in the clear: a set of highly meaningful sentences ("meaningful") and a set of sentences that retained appropriate syntactic structure but lacked semantic context ("anomalous"). The primary distinction between these sets of sentences was the degree to which semantic context could be used to support sentence recognition. Participants also completed testing using a battery of neurocognitive assessments of working memory capacity, inhibition–concentration, speed of lexical access, and nonverbal reasoning. Results of that study demonstrated that inhibition–concentration abilities predicted recognition accuracy for meaningful sentences while controlling for performance on the anomalous sentences; the authors interpreted this finding as inhibition–concentration abilities playing a role in the use of semantic context during sentence recognition for adult CI users. Speed of lexical access and nonverbal reasoning were also found to predict recognition accuracy for the anomalous sentences. Although that study revealed a relationship between inhibition–concentration and use of semantic context in sentence recognition, findings from adult CI users may not be generalizable to NH listeners hearing unfamiliar noise-vocoded speech. Moreover, that study did not specifically investigate how aging may impact the processes that come to bear to support the use of semantic context during sentence recognition.

How aging impacts the ability of listeners to process speech under adverse listening conditions, and particularly to use top-down processing to recognize speech, is still relatively unknown. From a theoretical standpoint, a better understanding of top-down processing—and the neurocognitive and language functions that underlie top-down processing—will provide a more detailed picture of how individuals tackle the task of recognizing speech under adverse listening conditions. To understand the potential aging effects, it is important to evaluate the underlying contributing neurocognitive factors. Moreover, it would be valuable to know whether the mechanisms that underlie speech recognition and top-down processing differ for older versus younger listeners. Perhaps older listeners rely on the same mechanisms as younger adults but just perform them less efficiently. In contrast, older listeners may apply their linguistic knowledge and neurocognitive resources in a fundamentally different way than younger adults. From a clinical standpoint, identifying the mechanisms by which older listeners apply language knowledge through top-down processing may suggest potential rehabilitation targets for individuals with hearing loss, such as identifying particular neurocognitive functions that might be targeted for enhancement through training.

This Study

In this study, we investigated sentence recognition and top-down semantic context effects on older and younger near-NH participants listening to noise-vocoded sentences that were meaningful versus anomalous. Noise-vocoded speech served as a novel adverse listening condition with which participants would not be familiar from previous listening experience. Participants were also tested on a battery of neurocognitive measures assessing working memory capacity, inhibition–concentration, speed of lexical access, and nonverbal reasoning, as well as a measure of word familiarity (serving as a proxy for vocabulary knowledge or crystallized intelligence). Our first hypothesis, based on expected overall poorer auditory processing and neurocognitive functioning in older as compared with younger adults, was that older adults would perform more poorly overall on both types of vocoded sentences as compared with their younger peers. However, previous work has demonstrated that, in some forms of adverse listening, older adults are able to benefit from top-down semantic context at least as much as younger adults. Thus, for our second hypothesis, two alternative hypotheses were tested. On the one hand, if older adults are able to compensate effectively while listening to novel noise-vocoded stimuli, older adults will make use of semantic context equally to or even more so than their younger peers. On the other hand, if older adults are not able to compensate sufficiently in the processing of unfamiliar vocoded speech, then we would expect to observe less benefit from semantic context in older compared with younger listeners. Our third hypothesis was that recognition accuracy on meaningful versus anomalous vocoded sentences (as well as the difference score, reflecting "context gain") would be determined by specific neurocognitive skills. More specifically, we predicted that specific skills based on the neurocognitive, language, and hearing profiles of the listeners would contribute to performance on meaningful versus anomalous sentence recognition abilities.

Materials and Method

Participants

A total of 88 adults participated in this study; 45 were younger adults between the ages of 18 to 35 years (YNH) and 39 were older adults between the ages of 50 to 85 years (ONH) with "near-normal" hearing. Because enrolling older adults with normal pure-tone thresholds was challenging, the "near-normal" pure-tone average (PTA) criterion for frequencies 0.5, 1, 2, and 4 kHz was relaxed to 30 dB HL or better in both ears, as per Moberly et al. (2018). Three older participants did not meet the near-normal PTA criterion, so their data were excluded prior to analysis. Lastly, one ONH participant demonstrated Stroop inhibition–concentration response times that were > 3 *SD*s longer than the mean, so this participant's data were excluded from analyses. Thus, 45 YNH and 39 ONH participants were included in analyses. All participants were recruited from the Otolaryngology Department at The Ohio State University as patients with nonotologic complaints or using ResearchMatch, a national research recruitment service. All included participants passed the Mini-Mental State Examination (MMSE), which is a validated cognitive screening assessment tool (Folstein et al., 1975), with a score of ≥ 26 on the MMSE. All participants were also assessed for basic word-reading ability to ensure general language proficiency using the Word Reading subtest of the Wide Range Achievement Test–Fourth Edition (WRAT-4; Wilkinson & Robertson, 2006). All 84 participants whose data were included in analyses demonstrated WRAT-4 standard scores of ≥ 80, suggesting reasonably normal general language proficiency. Because some tasks required the participants to look at a computer monitor or complete paper forms, a final screening test of near-vision was done, and all but six participants had corrected near-vision of better than or equal to 20/30. The participants who demonstrated near-vision worse than 20/30 all had reading standard scores on the WRAT-4 of better than 80, suggesting sufficient vision abilities to be included in data analyses. All participants spoke American English as their native language and had at least a high school diploma. Average demographic, audiologic, and screening data for the 84 participants included in analyses are shown in Table 1, along with results of independent-samples *t* tests comparing the two groups. These *t* tests demonstrated significant group differences in age (ONH > YNH) and PTA (ONH > YNH), whereas MMSE and WRAT-4 scores were not significantly different between groups.

General Approach and Measures

Participants were tested in one session lasting approximately 2 hr. All tasks were performed in a soundproof booth or sound-treated testing room. Participants completed two sentence recognition tasks and a battery of nonauditory neurocognitive and linguistic measures. Auditory speech stimuli were presented sound field in quiet at 68 dB SPL via a Roland MA-12C speaker (Roland Corp. placed 1 m in front of the speaker at 0° azimuth. Neurocognitive and linguistic tasks included measures of working memory capacity, inhibition–concentration, speed of lexical access, nonverbal reasoning, and vocabulary knowledge. For sentence recognition tasks and the measure of speed of lexical access, participant responses were video- and audio-recorded to allow later scoring. Participants wore vests with FM transmitters that sent signals to receivers connected to a video camera. Responses for these tasks were scored offline. Two experimenters independently scored 25% of responses to assess reliability. For the computerized tasks of working memory capacity, inhibition–concentration, and nonverbal reasoning, participants entered responses directly into the computer, which generated output scores. Audiometry was performed using a Welch Allyn TN262 audiometer with TDH-39 headphones. The measure of vocabulary knowledge (WordFAM) was completed in written fashion on paper and scored later. All participants provided informed written consent prior to participation and received $15 per hour for their time. Institutional review board (IRB) approval was obtained by the Biomedical Sciences IRB of The Ohio State University.

Sentence Recognition

Participants completed two sentence recognition tasks involving semantically meaningful or meaningless (anomalous) sentences. Each sentence type was presented within a single block, and order of blocks was counterbalanced among participants.

Semantically Meaningful Sentences

The recognition of semantically meaningful sentences was assessed using sentences from the Institute of Electrical and Electronics Engineers (IEEE) corpus (IEEE, 1969). Each sentence consisted of five key words in a semantically rich context (e.g., "The boy was there when the sun rose"). Participants were presented with a single sentence and were asked to repeat what they understood without stimulus repetition. Listeners were presented with two training sentences without feedback and then 28 test sentences spoken by the same male talker. Scores were computed as percent total correct words for all words in sentences.

Semantically Anomalous Sentences

The recognition of semantically anomalous sentences was assessed using modified versions of sentences from the

Table 1. Participant demographics, speech recognition, neurocognitive, and language scores for 45 young normal-hearing (YNH) and 39 older near-normal-hearing (ONH) participants, along with results of independent-samples *t* tests comparing groups.

	YNH (n = 45)			ONH (n = 39)				
Variable	*M*	(*SD*)	Range	*M*	(*SD*)	Range	*t*	*p*
Demographics								
Age (years)	25.0	(4.0)	18–34	66.5	(6.5)	50–81	–35.7	**< .001**
MMSE (raw score)	29.4	(1.1)	26–30	29.4	(0.8)	26–30	0.30	.765
Word Reading (WRAT-4 standard score)	103.0	(9.2)	84–130	101.8	(9.5)	82–126	0.47	.549
Better ear pure-tone average (dB HL)	4.7	(4.8)	–3.8–18.8	14.6	(5.5)	6.3–28.8	–8.9	**< .001**
Speech recognition								
Meaningful sentences (% words correct)	74.6	(9.8)	45.5–88.4	66.5	(11.9)	40.6–88.8	3.39	**.001**
Anomalous sentences (% words correct)	47.3	(11.8)	20.9–70.2	39.2	(14.3)	9.3–61.4	2.89	**.005**
Neurocognitive tasks								
Digit span (no. of items correct)	60.3	(18.9)	31–114	48.4	(17.2)	20–100	3.00	**.004**
Stroop interference (ms)	111.9	(120.5)	–146.8–546.3	283.0	(190.6)	–3.1–816.9	4.94	**< .001**
TOWRE-2 Words (% words correct)	82.5	(12.8)	62–100	77.5	(9.3)	51–100	2.02	**.046**
Raven's Nonverbal Reasoning (no. of items correct)	21.8	(5.9)	10–37	13.3	(5.9)	6–26	6.65	**< .001**
Language								
WordFAM (score)	4.6	(0.84)	2.9–6.1	5.3	(0.81)	3.6–6.5	–4.04	**< .001**

Note. *p* values are bolded where significant at $p < .05$. MMSE = Mini-Mental State Examination; WRAT-4 = Wide Range Achievement Test–Fourth Edition; TOWRE-2 = Test of Word Reading Efficiency–Second Edition.

IEEE corpus (Herman & Pisoni, 2000; Loebach & Pisoni, 2008). Sentences were phonetically balanced, syntactically correct, and semantically meaningless (e.g., "The deep buckle walked the old crowd"). As was done for the meaningful sentences, listeners were presented with two training sentences without feedback and then 28 test sentences spoken by the same male talker. Scores were computed as percent total correct words for all words in sentences.

Noise Vocoding

A MATLAB script that was created for another study (Moberly et al., 2018) was used to vocode sentences. Using this script, a white noise vocoder was implemented with eight spectral bands to create each degraded condition. A frequency range of 250–8000 Hz was used, along with a low-frequency cutoff of 300 Hz, to mimic the typical upper limit of pitch perception in actual CI users. The temporal envelopes were extracted using half-wave rectification and a fourth-order, zero-phase, low-pass filter.

Nonauditory Neurocognitive and Language Measures

Working Memory Capacity

A computerized Visual Digit Span task was used to measure working memory capacity based on the original auditory digit span from the Wechsler Intelligence Scale for Children–Fourth Edition Integrated (Wechsler, 2004) and previously used in adults with CIs (Moberly & Reed, 2019). Visual stimuli were used to eliminate potential effects of audibility on performance. Sequences of digits were presented visually on a computer screen, one at a time, and participants were asked to reproduce the lists of digits in correct serial order by touching the screen. Total number of correct digits in correct serial order was used in analyses.

Inhibition–Concentration

A computerized visual version of a verbal Stroop task was used, which is publicly available (http://www.millisecond.com). Participants were presented with color words one at a time on a computer screen and were asked to push a keyboard button identifying the color of the text of the word shown. Scoring was automatically performed by the computer at the time of testing after the participant directly entered responses. Response times were computed for correct responses to congruent words (automatic word reading; e.g., the word "Green" was shown in green text) and to incongruent words (inhibition of word reading to concentrate on ink color; e.g., the word "Red" was shown in green text). An interference score was computed as the response time to incongruent words minus the response time to congruent words, with larger scores representing greater interference (i.e., poorer inhibition–concentration), and this interference score was used in analyses.

Speed of Lexical Access

The Test of Word Reading Efficiency–Second Edition (TOWRE-2) was used to assess participants' speed of verbal processing for written materials (Torgesen et al., 1999). Participants were asked to read as many words as accurately as possible from a list of 108 words within 45 s. Percent correct words served as the measure used in analyses.

Nonverbal Reasoning

A computerized version of Raven's Progressive Matrices was used (Raven, 2000). This task presented geometric designs in a matrix where each design contained a missing piece, and participants were asked to complete the pattern by selecting a response box that completed the design. Participants were encouraged to guess if they were unable to determine the correct response. An abbreviated version of Raven's test was conducted over 10 min. Raw score (items correct) was used as the measure of nonverbal reasoning.

Vocabulary Size

To serve as a proxy for vocabulary knowledge and crystallized intelligence, participants completed a self-report written word familiarity task, the WordFAM test (Pisoni, 2007). In the WordFAM test, participants rated 50 low-, medium-, and high-frequency English words (150 total words) from 1 = *have never seen the word before* to 7 = *recognize word and are confident of its meaning*. A mean familiarity score across all words was computed and used in analyses.

Data Analyses

Interscorer reliability was assessed for tests that involved audiovisual recording and offline scoring of responses. All responses were scored by one trained scorer and then scored again by a second scorer for 25% of all participants (n = 22). With interscorer reliability greater than 90% (range: 94%–100%) for the MMSE, word reading, WordFAM, sentence recognition, and neurocognitive tests, the scores from the initial scorer were used in all analyses.

Statistical analyses were performed using SPSS software, Version 26 (IBM). Sentence recognition scores were screened for normal distributions and homogeneity of variances using Kolmogorov–Smirnov and Shapiro–Wilk tests of normality, as well as review of *Q–Q* plots of standardized residuals. Scores on meaningful and anomalous sentences were not normally distributed and demonstrated negative skew; following arcsine transformations, which were used as variance-stabilizing transformations, scores on these variables were normally distributed. The transformed sentence recognition variables were used in all subsequent analyses, but nontransformed scores are shown in tables and figures for interpretability. For all analyses, an alpha of .05 was set for significance.

To test our first and second hypotheses, a mixed-design analysis of variance (ANOVA) was carried out on recognition of words in sentences with group (ONH vs. YNH) as a between-subjects factor and material (meaningful vs. anomalous sentences) as a within-subject factor. Although all listeners were expected to perform better on meaningful sentences than anomalous sentences (i.e., a main effect of material), a main effect of group would be consistent with our first hypothesis that ONH participants would perform worse than their YNH peers on vocoded sentence recognition. A Material × Group interaction would inform us regarding our second hypothesis (or its alternative) that ONH listeners would use semantic context less (or more) than their YNH peers. To test our third hypothesis—that while accounting for age (i.e., across groups), recognition performance on meaningful versus anomalous vocoded sentences would be predicted by specific neurocognitive skills—two separate multivariable linear regression analyses were performed to determine which neurocognitive functions would predict either meaningful or anomalous sentence recognition as outcomes. A third multivariable regression analysis was also performed specifically to evaluate as outcome the "context gain score," computed as the difference between raw recognition scores for meaningful sentences versus anomalous sentences (meaningful minus anomalous). For each of these three regression analyses, PTA was entered as a covariate, based on the expected finding that PTA would be different between the groups. Neurocognitive measures (working memory capacity, inhibition–concentration, speed of lexical access, and nonverbal reasoning) were then entered together as the main predictors of interest, along with WordFAM score (our proxy for vocabulary size/crystallized intelligence).

Lastly, to examine whether specific sets of skills based on the neurocognitive, language, and hearing profiles of listeners would contribute to meaningful versus anomalous sentence recognition abilities, we performed exploratory (i.e., data-driven) cluster analyses across all 84 listeners from both YNH and ONH groups together. This approach was taken to determine whether subprofiles of listeners could be identified, suggested by clustering patterns of listeners based on their hearing and neurocognitive–linguistic skills. These analyses were conducted on PTA, context gain scores, and neurocognitive–linguistic scores (working memory capacity, inhibition–concentration, speed of lexical access, nonverbal reasoning, and WordFAM). To evaluate the relevance of the identified subprofiles of listeners to noise-vocoded sentence recognition, we then compared the participants in the resulting clusters for their performance on meaningful and anomalous sentences, with the prediction that the different clusters would demonstrate characteristic differences in sentence recognition performance. Finally, to determine how aging might influence different subprofiles of listeners, we examined age differences across participants in the resulting clusters.

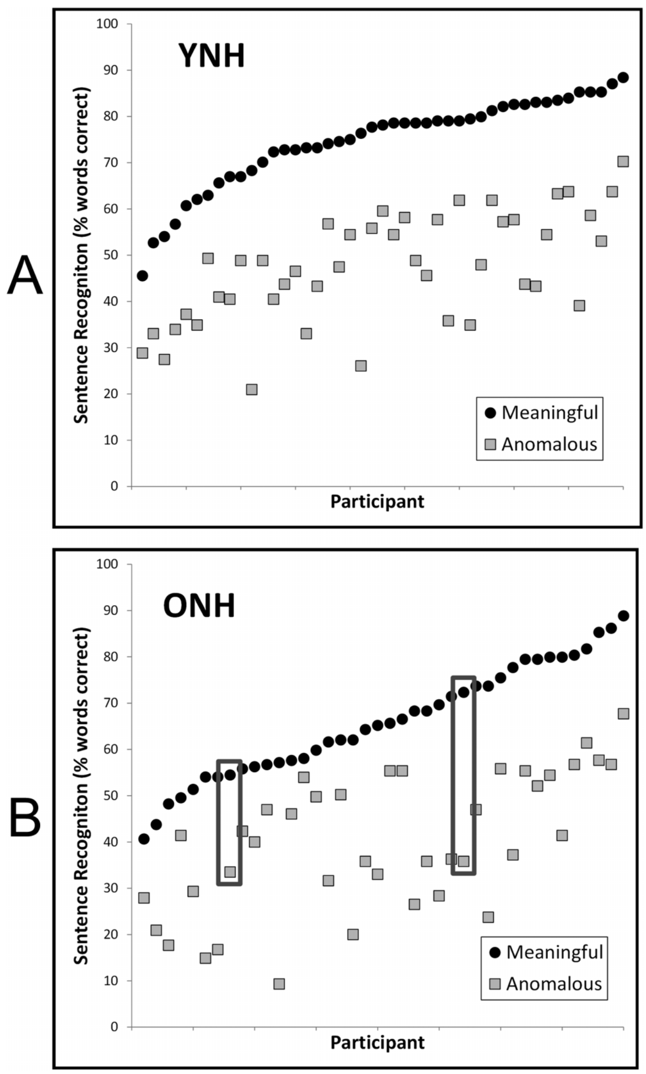
Results

Scores on all sentence recognition measures and neurocognitive–linguistic assessments are provided in Table 1. Mean sentence recognition scores were 74.6% (SD = 9.8) and 66.5% (SD = 11.9) for meaningful sentences for YNH and ONH, respectively, and 47.3% (SD = 11.8) and 39.2% (SD = 14.3) for anomalous sentences for YNH and ONH, respectively. Individual sentence recognition scores are plotted in Figure 1A for YNH listeners and Figure 1B for ONH participants, arranged from poorest to best meaningful sentence score, demonstrating consistently better scores for meaningful sentences than for anomalous sentences but with substantial variability across participants.

Next, the mixed-design ANOVA was carried out. As predicted, results demonstrated a main effect of material, $F(1, 82) = 556.6$, $p < .001$, with performance on meaningful sentences being higher than performance on anomalous sentences. Also as predicted, a main effect of group was also revealed, $F(1, 82) = 12.0$, $p = .001$, with performance by YNH being higher than performance by ONH listeners. However, the Group × Material interaction was not significant, $F(1, 82) = .012$, $p = .915$. Consistent with our first hypothesis, these results support that ONH listeners perform more poorly on vocoded sentence materials (both meaningful and anomalous) than their YNH peers. However, regarding our second question, the lack of a significant Group × Material interaction suggests that the relative benefit of sentence context was not different for ONH and YNH listeners.

Next, three multivariable linear regression analyses were performed as described above. Prior to these analyses, a series of Pearson correlation analyses on the included predictors (working memory capacity, inhibition–concentration, speed of lexical access, nonverbal reasoning, PTA, and WordFAM) were carried out in order to evaluate the relation among predictors and remove any strongly correlated factors ($r > .70$; Taylor, 1990). None of the factors were strongly correlated (r magnitude ranged between .01 and .51), as shown in Table 2. Therefore, all factors were included as predictors in the multivariable linear regression analyses. The first analysis (results shown in Table 3), with meaningful sentence recognition as the outcome, revealed that the model was significant, $F(6, 74) = 8.05$, $p < .001$, with an R^2 of .395. The only significant independent predictor of meaningful sentence recognition was Raven's score of nonverbal

Figure 1. Speech recognition scores for meaningful and anomalous sentences for (A) 45 young normal-hearing (YNH) participants and (B) 39 older near-normal-hearing (ONH) participants. Boxes in B outline scores for two individual participants who have nearly the same anomalous sentence recognition scores but quite different meaningful sentence scores.



reasoning (β = .42, p = .001). The second analysis (results shown in Table 3), with anomalous sentence recognition as the outcome, revealed that the model was significant, $F(6, 74) = 5.16$, $p < .001$, with an R^2 of .295. For this model, there were two predictors that were independently significant: PTA (β = −.32, p = .012) and Raven's score of nonverbal reasoning (standardized β = .26, p = .043). Finally, the third analysis, with context gain score (meaningful minus anomalous) as the outcome, revealed that the model was not significant (p = .851). Thus, results of these multivariable analyses demonstrated that this set of predictors explained approximately 40% of the variance in meaningful sentence recognition, with nonverbal reasoning serving as the only significant independent predictor. The same set of predictors explained approximately 30% of the variance in anomalous sentence recognition, with both PTA and nonverbal reasoning serving as significant independent predictors. Finally, this set of predictors did not explain variance in magnitude of context use.

The finding of enormous variability in the magnitude of difference between the plotted meaningful and anomalous sentence scores (the context gain) among individual listeners in both groups (see Figures 1A and 1B) supported taking an individual differences approach to exploring the results. Despite a lack of a significant multivariable linear regression model above to explain context gain score, we aimed to further explore the broad individual differences in context gain demonstrated among participants and specifically how cognitive compensation mechanisms relate to the recognition of noise-vocoded sentences. For example, consider the two ONH participants whose data are outlined in Figure 1B. These participants have nearly the same anomalous sentence recognition score (approximately 35%) but very different meaningful sentence scores (54% vs. 72%). This finding suggests that these two listeners benefit from semantic context to different degrees to understand noise-vocoded sentences and, as such, are possibly using different strategies for meaningful sentence recognition.

To explore this concept, we performed exploratory cluster analyses on YNH and ONH participants using SPSS. Given that none of the factors were strongly correlated, as reported above, all factors were included in the cluster analysis and were standardized to control for unequal scaling of factors, resulting in a distribution with a mean of 0 and a standard deviation of 1. To determine how many clusters were appropriate for the cluster solution, a hierarchical cluster analysis using Ward's method was first conducted (Ward, 1963). Ward's method can inform the number of clusters by evaluating the merging cost associated with forming additional clusters. A large increase in the cluster agglomeration coefficient—indicating a large merging cost—was used to determine the number of clusters. The hierarchical clustering analysis suggested a solution with four clusters based on the interpretation of a large increase or elbow in linkage distance coefficients at four clusters. A four-cluster solution was then generated by k-means (nonhierarchical) cluster analysis to determine which individual listeners belonged to each group. The resulting clusters resulted in groups of 21, 14, 20, and 26 individual listeners, with group means (raw scores) provided in Table 4.

The resulting clusters were compared across noise-vocoded sentence recognition measures to evaluate performance by the four clusters (subprofiles) of listeners. Figure 2 shows four panels representing scatter plots of

Table 2. Results of Pearson correlations among predictor measures for the entire group of young normal-hearing and older near-normal-hearing participants.

Predictor		Digit span	Stroop	TOWRE-2	Raven's	PTA	WordFAM
Digit span (no. of items correct)	*r*	1	**−.31**	**.25**	**.34**	−.12	.01
	p	—	**.004**	**.025**	**.002**	.281	.980
Stroop interference (ms)	*r*		1	−.21	**−.50**	**.44**	.06
	p		—	.057	**< .001**	**< .001**	.601
TOWRE-2 Words (% words correct)	*r*			1	**.29**	−.20	**.23**
	p			—	**.018**	.073	**.040**
Raven's nonverbal reasoning (no. of items correct)	*r*				1	**−.51**	−.04
	p				—	**< .001**	.737
Better ear PTA (dB HL)	*r*					1	**.26**
	p					—	**.021**
WordFAM (score)	*r*						1
	p						—

Note. Pearson's *r* and *p* value are bolded where $p < .05$. TOWRE-2 = Test of Word Reading Efficiency–Second Edition; PTA = pure-tone average.

data for the four clusters of participants: age versus better ear PTA, meaningful versus anomalous sentence recognition, digit span versus Raven's, and Stroop versus TOWRE performance. One-way ANOVAs on sentence recognition scores with cluster as the factor showed a significant effect of cluster on recognition of both meaningful, $F(3, 80) = 5.3$, $p = .002$, and anomalous sentences, $F(3, 80) = 6.2$, $p = .001$. For meaningful sentences, post hoc Tukey's tests revealed that Cluster 4 was significantly more accurate than Cluster 1 ($p = .003$) and Cluster 2 ($p = .018$). No other comparison reached significance. For anomalous sentences, post hoc Tukey's tests revealed that Clusters 2 and 4 were significantly more accurate than Cluster 1 (Cluster 2, $p = .009$; Cluster 4, $p = .001$). No other comparison reached significance.

Finally, to determine how age relates to the subprofiles of listeners, a one-way ANOVA showed a significant effect of cluster on age, $F(3, 80) = 30.5$, $p < .001$. Post hoc Tukey's tests revealed that Cluster 1 was significantly older than Clusters 3 ($p < .001$) and 4 ($p < .001$) and that Cluster 2 was significantly older than Clusters 3 ($p < .001$) and 4 ($p < .001$).

Taken together, Cluster 4 appears to demonstrate the strongest meaningful and anomalous noise-vocoded sentence recognition, Cluster 2 demonstrates poorer meaningful but relatively good anomalous noise-vocoded sentence recognition, and Cluster 1 consistently demonstrates the poorest overall performance. The highest-performing cluster (Cluster 4) shows stronger neurocognitive skills, including the strongest inhibition–concentration, working

Table 3. Results of multivariable linear regression analyses for the entire group of young normal-hearing and older near-normal-hearing participants, with meaningful sentence score as dependent measure in the upper panel and anomalous sentence score as dependent measure in the lower panel.

Predictors	Unstandardized *B*	Coefficient *SE*	Standardized β	*t*	Sig. (*p*)
Dependent measure: Meaningful sentence recognition (% words correct, arcsine transformed)					
Digit span (no. of items correct)	0.002	0.001	.133	1.35	.182
TOWRE-2 Words (% words correct)	−0.001	0.001	−.073	−0.67	.506
Stroop interference (ms)	−0.044	0.217	−.020	−0.20	.840
Raven's nonverbal reasoning (no. of items correct)	0.015	0.004	.420	3.60	**.001**
Better ear pure-tone average (dB HL)	−0.007	0.004	−.183	−1.58	.118
WordFAM (score)	0.032	0.028	.113	1.15	.252
Dependent measure: Anomalous sentence recognition (% words correct, arcsine transformed)					
Digit span (no. of items correct)	0.001	0.002	.088	0.82	.413
TOWRE-2 Words (% words correct)	−0.001	0.001	−.021	−0.18	.859
Stroop interference (ms)	−0.019	0.267	−.007	−0.07	.945
Raven's nonverbal reasoning (no. of items correct)	0.010	0.005	.259	2.06	**.043**
Better ear pure-tone average (dB HL)	−0.013	0.005	−.322	−2.58	**.012**
WordFAM (score)	0.044	0.034	.134	1.27	.207

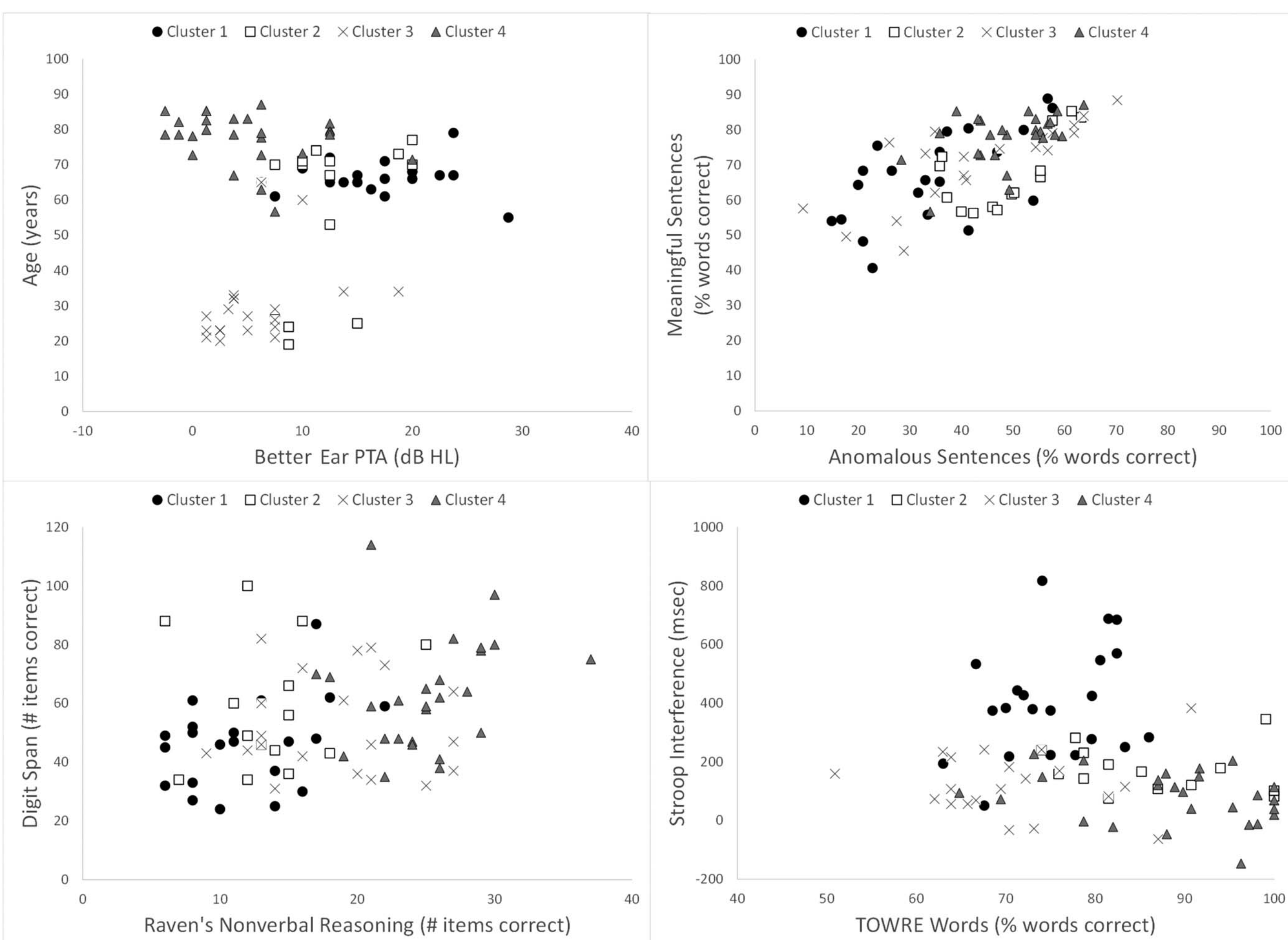
Note. *p* values are bolded where $p < .05$. TOWRE-2 = Test of Word Reading Efficiency–Second Edition.

Table 4. Speech recognition and neurocognitive–linguistic scores for the four resulting clusters from cluster analysis approach including all 84 participants.

Variable	Cluster 1		Cluster 2		Cluster 3		Cluster 4	
	M	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
Speech recognition								
Meaningful sentences (% words correct)	66.5	(12.9)	67.2	(10.3)	70.8	(11.7)	77.7	(7.1)
Anomalous sentences (% words correct)	34.5	(13.4)	48.4	(9.3)	43.2	(16.8)	49.2	(8.7)
Neurocognitive tasks								
Digit span (no. of items correct)	46.3	(15.2)	58.9	(22.2)	52.8	(16.9)	62.9	(18.7)
Stroop interference (ms)	398.2	(189.9)	172.8	(78.9)	125.6	(108.1)	79.8	(88.6)
TOWRE-2 Words (% words correct)	75.2	(6.4)	86.0	(9.2)	70.8	(9.5)	88.6	(10.2)
Raven's nonverbal reasoning (no. of items correct)	11.7	(4.6)	13.6	(4.6)	18.5	(5.5)	25.1	(4.3)
Language								
WordFAM (score)	5.1	(0.81)	5.3	(0.74)	4.1	(0.68)	5.3	(0.74)
Demographics/audiologic								
Age (years)	64.6	(9.8)	58.1	(20.7)	30.3	(11.9)	31.2	(16.0)
Better ear PTA (dB HL)	16.1	(6.0)	13.2	(4.3)	5.7	(4.4)	5.1	(5.6)

Note. TOWRE-2 = Test of Word Reading Efficiency–Second Edition; PTA = pure-tone average.

Figure 2. Scatter plots of data for the four clusters of participants. Upper left panel: age versus better ear PTA. Upper right panel: meaningful versus anomalous sentence recognition. Lower left panel: digit span versus Raven's. Lower right panel: Stroop versus TOWRE performance. PTA = pure-tone average; TOWRE = Test of Word Reading Efficiency.



memory capacity, speed of lexical access, and nonverbal reasoning. Vocabulary size was also relatively large for Cluster 4. Cluster 4 is also younger in age than at least Clusters 1 and 2. Cluster 1 consistently shows poorer noise-vocoded sentence recognition, at least compared with Cluster 4. Cluster 1 is older, has relatively high PTAs, and shows relatively poor neurocognitive skills. Thus, differences in Clusters 4 and 1 suggest a role for age in noise-vocoded sentence recognition, as well as basic neurocognitive–linguistic abilities, similar to the above regression analyses.

However, Clusters 1 and 4 show similar context benefit, but with vastly different recognition accuracy levels, suggesting little role for age and certain neurocognitive skills in the use of context. To specifically examine context gain, a useful comparison is between Clusters 1 and 2, since Cluster 2 shows similar scores for meaningful sentences but relatively better scores for anomalous sentences. Indeed, only Cluster 2 shows a relatively low-context gain. Clusters 1 and 2, with similar performance on meaningful sentences, show similar age, PTA, and vocabulary size, suggesting that both groups are able to take advantage of larger vocabulary sizes to compensate for degraded speech in meaningful sentences. However, Cluster 2 shows better inhibition–concentration, working memory, speed of lexical access, and nonverbal reasoning, potentially contributing to the more accurate scores for anomalous sentences. Another useful comparison is between Clusters 2 and 3, who again show similar meaningful sentence performance but differing anomalous performance. Cluster 3 represents relatively younger participants, with good PTAs, inhibition–concentration, and nonverbal reasoning. However, Cluster 3 also shows poorer working memory and speed of lexical access, suggesting that these functions may specifically contribute to anomalous sentence recognition. Cluster 3 showed relatively poorer vocabulary size; however, this did not impede them from taking advantage of context to recognize the meaningful sentences. However, their relatively good hearing may have reduced the relative reliance on semantic context. Thus, it appears that context gain, at least in the case of recognizing vocoded speech, does not rely on any one factor in particular. Rather, there may be multiple skills or sets of skills that can be used to compensate for noise-vocoded speech.

Discussion

The primary goal of this study was to investigate sentence recognition abilities and the use of semantic context in the recognition of noise-vocoded speech in older and younger adults with near-NH. Additionally, we sought to relate vocoded sentence recognition performance and use of semantic context to neurocognitive–linguistic skills that have previously been demonstrated to be associated with success in recognizing speech under adverse listening conditions.

Considering the aging-related declines that are common in both auditory processing and neurocognitive functioning in older adults, our first hypothesis was that ONH listeners would perform more poorly than their YNH peers on both types of noise-vocoded sentence materials. The results of this study supported that hypothesis. Related to our second hypothesis, however, ONH participants as a group made use of semantic context to a similar degree as their YNH peers, based on a lack of a significant Group × Material interaction in the mixed-design ANOVA. This finding suggests that older adults are able to capitalize on their crystallized intelligence (e.g., vocabulary knowledge) at least as well as younger listeners to use semantic context during sentence recognition. Notably, WordFAM scores, serving as a proxy for vocabulary size, were higher in the ONH group than their YNH peers, which is consistent with previous work (Verhaeghen, 2003). Although WordFAM was not a significant independent predictor in our regression models of meaningful or anomalous sentence recognition, it could be that larger vocabulary size assisted the ONH listeners in recognizing the degraded sentences they heard, allowing them to compensate not only for the degraded signal but also for relatively poorer hearing. Our findings are consistent with previous reports in which ONH are able to capitalize on semantic context at least as well as their YNH counterparts (Dubno et al., 2000; Kalikow et al., 1977; Madden, 1988; Pichora-Fuller, 2008; Pichora-Fuller et al., 1995; Smayda et al., 2016; Stine & Wingfield, 1994; Stine-Morrow et al., 1996) and extend these findings into recognition of noise-vocoded speech.

Beyond examining age-related differences, we also aimed to investigate whether relative recognition performance on meaningful versus anomalous vocoded sentences (i.e., context gain) would be determined by specific neurocognitive–linguistic skills. This was based on previous findings that certain neurocognitive skills have been found to be associated with recognition abilities for speech across varying types of adverse listening conditions (Başkent et al., 2016; Rönnberg et al., 2013; Schvartz et al., 2008), along with previous reports that specify the neurocognitive functions that contribute to individuals' use of semantic context (Federmeier & Kutas, 2005). We specifically examined working memory capacity, inhibition–concentration, lexical access speed, nonverbal reasoning, and vocabulary size.

Somewhat surprisingly, in this study, working memory capacity was not associated with meaningful or anomalous sentence recognition or use of context in ONH or YNH adults listening to noise-vocoded speech. This lack of an association may be due to our chosen measure of working memory capacity, the Visual Digit Span, which may serve as a better assessment of short-term memory as opposed to working memory, because the mental processing demands of forward digit span are minimal. Similarly, working memory capacity using digit span has previously not been found to predict sentence recognition in adult CI users (Moberly et al., 2017). A measure such as reverse digit span or reading span may provide a more accurate assessment of working memory capacity and may relate more to sentence recognition abilities.

In this study, we also did not find an association between inhibition–concentration ability (using Stroop) and vocoded sentence recognition or use of semantic context. This stands in contrast to the findings by Moberly and Reed (2019), who demonstrated that inhibition–concentration abilities were associated with greater use of semantic context in adult CI users. Similarly, speed of lexical access was not associated with sentence recognition or context gain here; in contrast, scores on the TOWRE-2 were found to be associated with anomalous sentence recognition by the adult CI users in the Moberly and Reed study. We hypothesized here that speed of lexical access should be a critically relevant information-processing operation during rapid processing of sentences. It is unclear why this association was not found in this study with vocoded speech. However, there may be something fundamentally different between recognizing degraded speech through a CI for experienced CI users and recognizing spectrally degraded speech through noise vocoding for adults with NH. For instance, perhaps speed of lexical access and inhibition–concentration relate more to relatively automatic processing by experienced CI users who are accustomed to listening to spectrally degraded speech. In contrast, NH listeners may need to rely more heavily on effortful, controlled processing to recognize novel, noise-vocoded stimuli, such that speed of lexical access contributes less to performance in NH listeners.

In contrast, we found in this study that nonverbal reasoning (i.e., fluid intelligence) on Raven's Progressive Matrices task predicted sentence recognition abilities for both meaningful and anomalous sentences. This result is consistent with findings by Mattingly et al. (2018), in which Raven's scores were found to predict recognition scores for high–talker variability Perceptually Robust English Sentence Test Open-Set sentences by adult CI users. This study extends those findings by identifying an association between nonverbal reasoning and both meaningful and anomalous sentence recognition for noise-vocoded speech. This general relationship of nonverbal reasoning with sentence recognition was further supported in our cluster analyses, with a general increase in Raven's scores across clusters from Cluster 1 to Cluster 4. Thus, it is likely that nonverbal reasoning plays a general role in recognition of noise-vocoded sentences, consistent with other forms of signal degradation such as listening through a CI (Mattingly et al., 2018; Tamati et al., 2019). That is, differences in cognitive functioning, potentially independent of aging, are associated with the ability to recognize vocoded speech. It is worth noting that Raven's measure of nonverbal reasoning used in this study included a 10-min time constraint to complete the task. Thus, it is possible that our Raven's measure is also tapping into aspects of information-processing speed.

Our cluster analyses provided interesting insight into the ways in which listeners tackle the problem of recognizing vocoded speech. In particular, the cluster analyses suggest that there may be more than one subprofile of listener that can maintain reasonably good speech recognition with supportive context. Indeed, although the four subprofiles differed in age, PTA, neurocognitive skills, and vocabulary size, they all were able to achieve relatively similar levels of meaningful sentence recognition. Even the poorest performing group (Group 1), with the overall poorest neurocognitive profile, achieved 66% correct for meaningful sentences. Although some listeners are able to capitalize on better hearing acuity (Cluster 3), others may rely upon top-down vocabulary knowledge (Clusters 1 and 2) to recognize speech in meaningful sentences. Assuming anomalous sentences rely heavily on acoustic–phonetic processing (i.e., bottom-up skills); this further suggests that good bottom-up processing may not be necessary or sufficient to achieve good meaningful sentence recognition. Thus, there may be more than one way to make use of supportive context in recognizing degraded meaningful sentences.

This study has several noteworthy limitations. First, the meaningful and anomalous sentence types used in this study primarily differed based on the presence or absence of semantic content; however, it is possible that our sentence materials may have also been different with regard to lexical content and/or syntactic structure. As such, measured context gain may have reflected additional linguistic factors. Second, the meaningful sentences we selected for this study were relatively lower in context compared with other sentence materials such as the R-SPIN Test (Bilger et al., 1984) sentences, so our findings may underestimate the impact of listeners' neurocognitive–linguistic skills on their use of semantic context. Third, listeners were only briefly exposed to noise-vocoded stimuli during two practice trials, without feedback, for each sentence material. If a group difference in use of semantic context had been identified in our analyses, it could be difficult to sort out whether this was a result of age-related differences in the ability to adapt rapidly to vocoded stimuli. As it stands, our results suggest that when confronted with novel spectrally degraded speech, the ONH and YNH groups made use of semantic context to similar degrees, such that this concern was somewhat ameliorated. Nonetheless, it could be that ONH listeners would perform more similarly to YNH listeners across both types of sentence materials if given more experience (i.e., more passive or active training) listening to noise-vocoded speech. Fourth, although the chosen measures to assess individual differences have a long history of established use and reliability (H. R. Burke, 1972; Richardson, 2007; Siegrist, 1997; Tarar et al., 2015), it should be acknowledged that it is possible that this study was underpowered to identify significant associations of these measures with speech perception abilities in our sample.

The clinical significance of this study is twofold. First, individuals—even older individuals—may be able to capitalize greatly on their language knowledge and top-down predictive coding during speech recognition. In particular, although this study focused on NH listeners, rehabilitative training for adults with hearing loss across the life span might be useful to improve use of linguistic context in understanding speech. Prospective interventional rehabilitation studies will be required to test this prediction. Second, findings from this study suggest that there are multiple ways that listeners deal with recognizing degraded speech. Specifically, our cluster analyses suggest that listeners may be able to rely on different skills, or sets of skills, to take advantage of linguistic context. That is, despite differences in fluid intelligence among individual younger and older listeners, all were able to achieve good meaningful sentence recognition, possibly through different top-down or bottom-up mechanisms. However, research from Winn (2016) suggests that the benefit from context in some listeners, who may rely on postdictive processing by making use of context information following the sentence, may nevertheless suffer from high listening effort and communication breakdowns with connected speech. More research should be carried out to identify factors that explain variability in how listeners use predictive and postdictive processing. Nevertheless, the finding from this study is encouraging, because it suggests that some listeners may be able to overcome certain hearing or neurocognitive deficits to maintain reasonably good communication abilities.

Conclusions

Findings from this study demonstrate that older adults with near-NH perform more poorly in recognizing noise-vocoded sentences than their younger peers. However, older adults are able to capitalize on their language knowledge (i.e., crystallized intelligence) to make use of semantic context in sentence recognition to the same degree as their younger counterparts. Nonverbal reasoning (i.e., fluid intelligence) appears to support sentence recognition, both for semantically meaningful and anomalous sentences. Additionally, individual listeners may vary in the strategies they use to make sense of meaningful noise-vocoded sentences. These findings further emphasize the interactive nature of bottom-up and top-down processes during speech recognition, especially under adverse listening conditions.

Data Availability Statement

Data are available on request from the authors.

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